System size and energy dependence of strangeness production from NA61/SHINE at the CERN SPS

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for the NA61/SHINE collaboration

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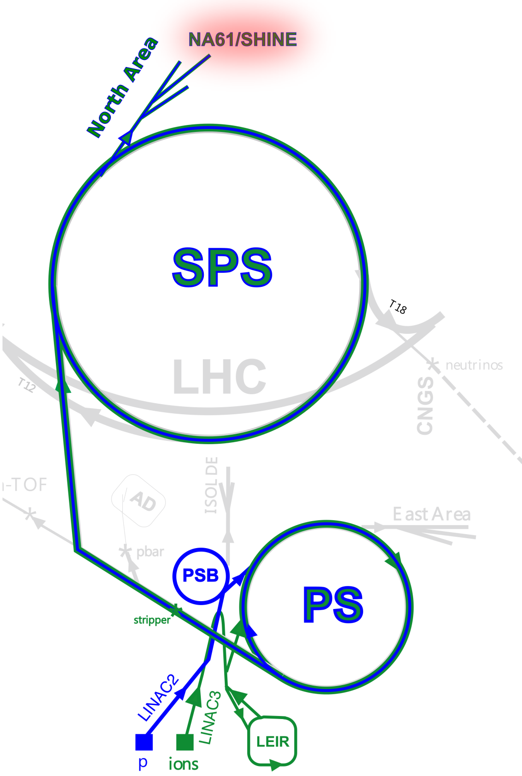
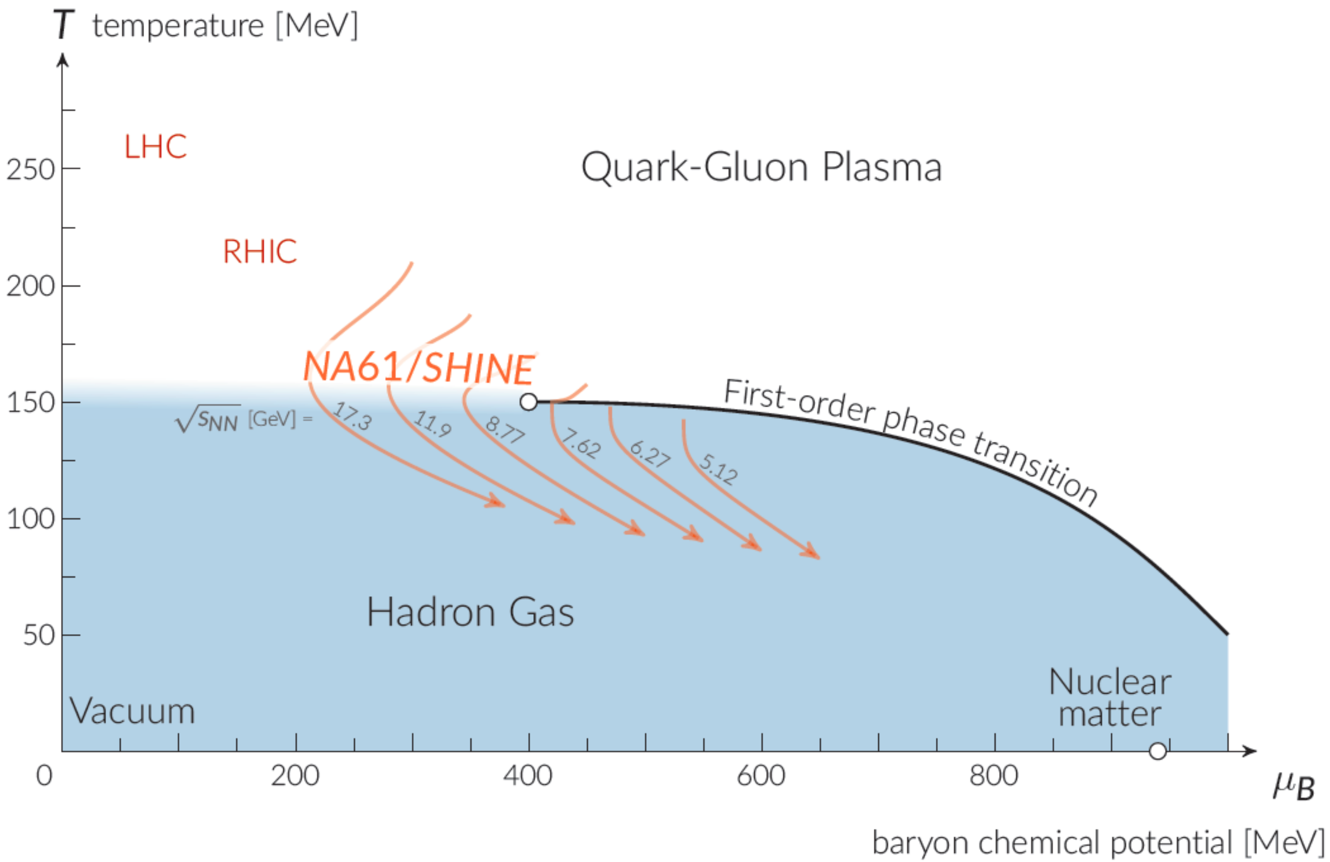
Zimányi School Winter Workshop on Heavy Ion Physics

NA61/SHINE experiment



- Particle physics experiment at SPS at CERN.
- Fixed target.
- 2 main physics goals:
  1. studies of proton–proton and nucleus–nucleus collisions to identify the **properties of the onset of deconfinement** and search of the critical point,
  2. reference measurements for neutrino and cosmic ray physics (hadron–nucleus collisions).

NA61/SHINE strong interaction programme



Plot from Maciej Lewicki

What is strangeness?

- Strangeness is a property of particle expressed as a quantum number.
- Total strangeness of particle: $S = -(n_s - n_{\bar{s}})$,
  n_s – number of strange quarks,
  $n_{\bar{s}}$ – number of strange antiquarks.
- Net strangeness of the system: $\sum_i S_i$.

- Net strangeness is conserved in all interactions except weak.
- We measure only **primary particles** – created in strong and EM interactions.
- No strange content in colliding nuclei.

→ In heavy ion collision **total net strangeness is 0**.

↓

In HIC strangeness is defined as a **number of $s\bar{s}$ pairs** ($N_{s\bar{s}}$).

Distribution of strangeness between hadrons

net strangeness conservation

$\bar{s} = s$

isospin symmetry: $K^+(u\bar{s}) \approx K^0(d\bar{s})$

isospin symmetry: $K^-(\bar{u}s) \approx \bar{K}^0(\bar{d}s)$

$K^0(d\bar{s}) \ggg \bar{\Lambda}(\bar{u}\bar{d}\bar{s})$

$\bar{K}^0(\bar{d}s) \approx \Lambda(uds)$

high baryon density

$\bar{\Lambda}(\bar{u}\bar{d}\bar{s}) \lll \Lambda(uds)$

– sensitive to strangeness content only

– sensitive to strangeness content and baryon density

How to measure strangeness

$$2\langle N_{s\bar{s}}\rangle = \langle \Lambda + \bar{\Lambda}\rangle + \langle K^+ + K^- + K^0 + \bar{K}^0\rangle + ...$$

$$2\langle N_{s\bar{s}}\rangle \approx \langle \Lambda\rangle + \langle K^+ + K^- + K^0 + \bar{K}^0\rangle,$$

$$\langle N_{s\bar{s}}\rangle \approx \langle \Lambda\rangle + \langle K^- + \bar{K}^0\rangle \approx \langle K^+ + K^0\rangle \approx 2\langle K^+\rangle.$$

How to measure entropy

Entropy $\sim \langle \pi\rangle$

$$\langle \pi\rangle = \langle \pi^+ + \pi^0 + \pi^-\rangle \approx 3\langle \pi^+\rangle$$

Experimental measure of strangeness to entropy ratio

$$\frac{\text{strangeness}}{\text{entropy}} \sim \frac{\langle N_{s\bar{s}}\rangle}{\langle \pi\rangle} \approx \frac{2\langle K^+\rangle}{3\langle \pi^+\rangle}$$

Strangeness at phase transition

$$\langle N_i \rangle = \frac{gV}{(2\pi)^3} \int \mathrm{d}^3 p \frac{1}{\exp\left(E/T\right) \pm 1}$$

confined matter

K-mesons

$g_K = 4$

$2M_K \approx 2 \times 500\mathrm{MeV}$
heavy – $M_K > T_c$

Phase transition
$T_c \approx 150\mathrm{MeV}$

quark-gluon plasma

s, $\bar{s}$ - quarks

$g_s = 12$

$2M_s \approx 2 \times 100\mathrm{MeV}$
light – $M_s < T_c$

$$\langle N_K \rangle = g_K V \left(\frac{M_K T}{2\pi} \right)^{\frac{3}{2}} \exp\left(-M_K/T\right)$$

$$\langle N_s \rangle = g_s V \frac{2\pi^2}{4 \cdot 45} \cdot T^3$$

Strangeness production is sensitive to phase transition.

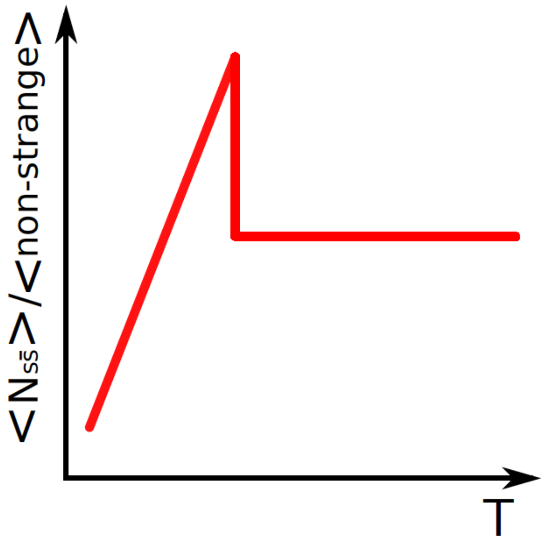
Strangeness/entropy at phase transition

hadron gas

$$\frac{\langle K \rangle}{\langle \pi \rangle} \sim \frac{(M_K T)^{\frac{3}{2}}}{T^3} \exp^{-\frac{M_K}{T}}$$

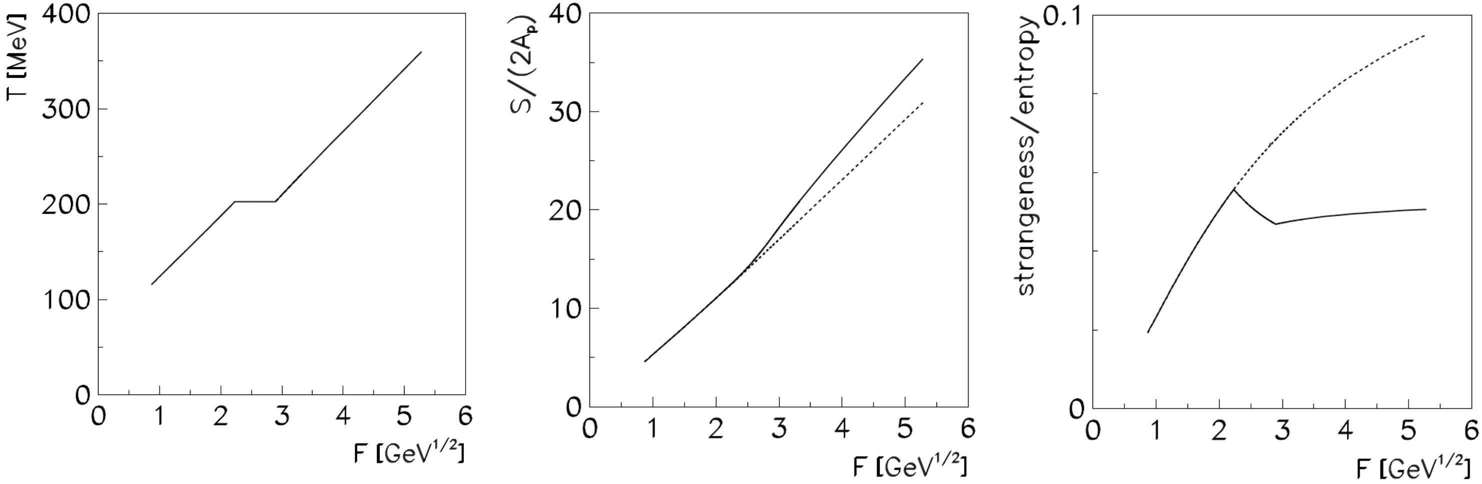
quark-gluon plasma

$$\frac{\langle s \rangle}{\langle u + d + g \rangle} \sim \frac{T^3}{T^3} = \mathrm{const}(T)$$



Signatures of the onset of deconfinement: SMES predictions

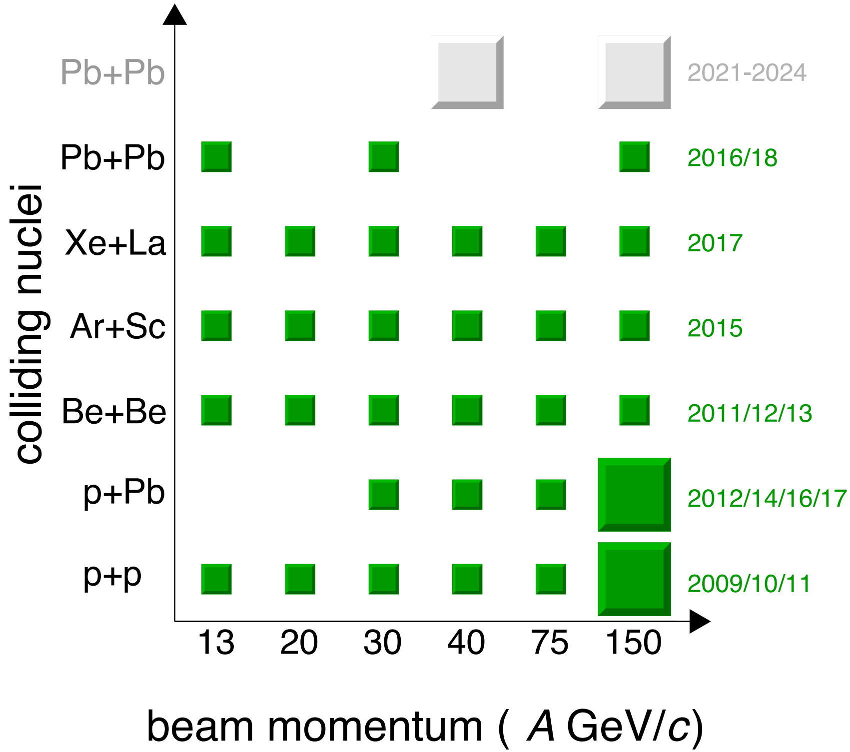
$F \approx (\sqrt{s_{NN}})^{1/2}$

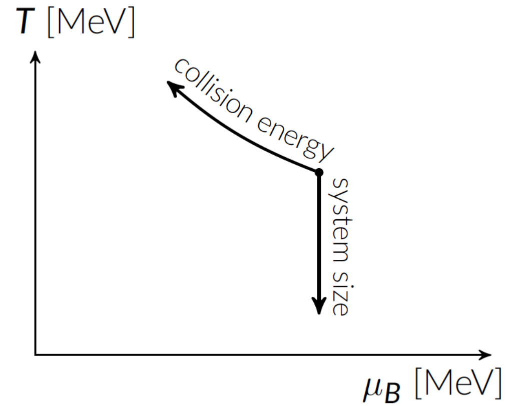


Step Kink Horn

Gaździcki, Gorenstein, Acta Phys. Pol. B 30, 2705 (1999)

NA61/SHINE 2D scan





Becattini, Manninen, Gaździcki
Phys. Rev. C 73, 044905 (2006)

Two-dimensional scan in collision energy and mass of the colliding nuclei.

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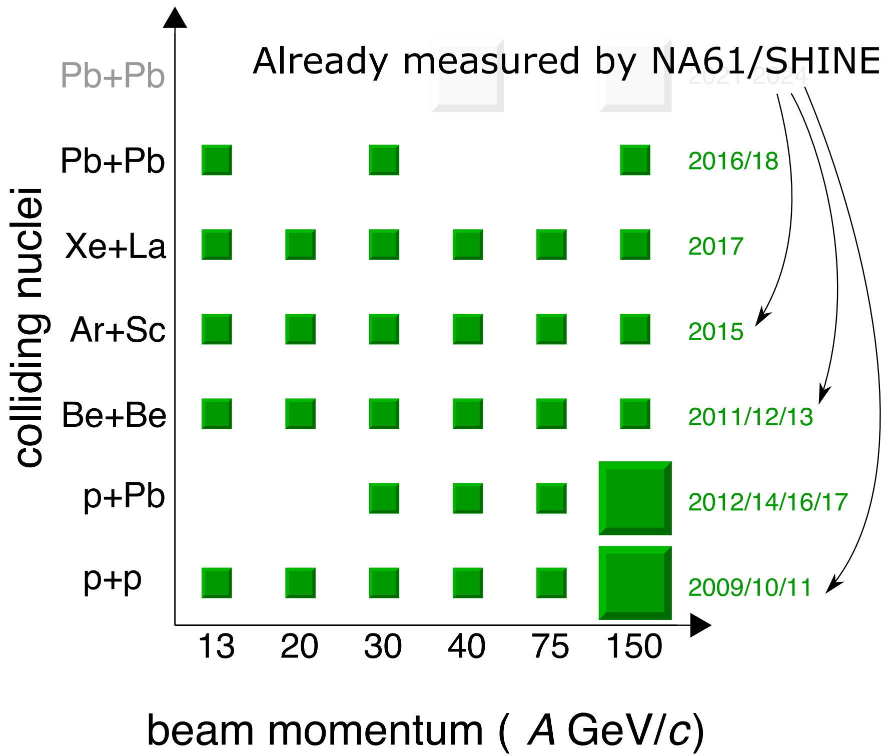

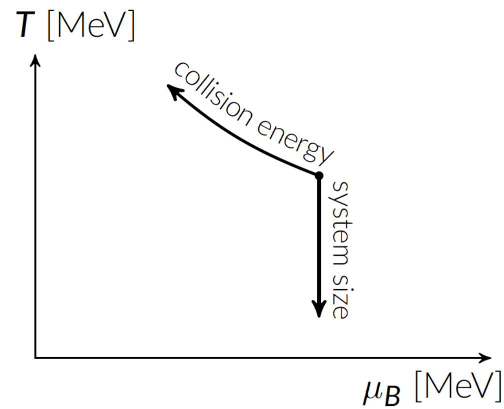

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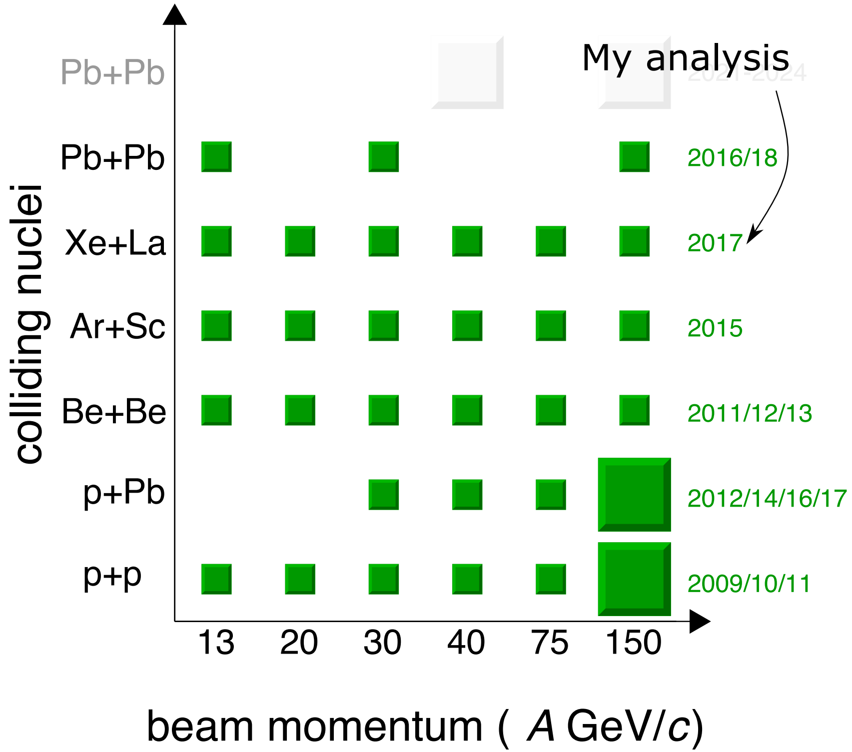

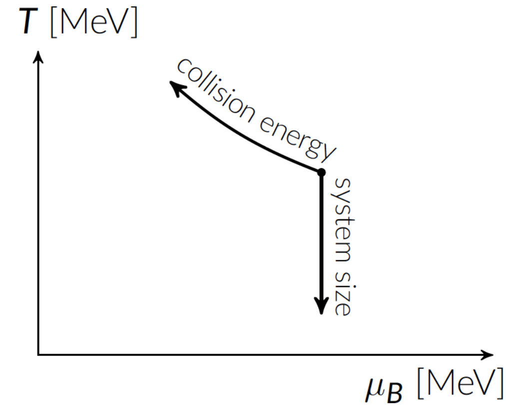

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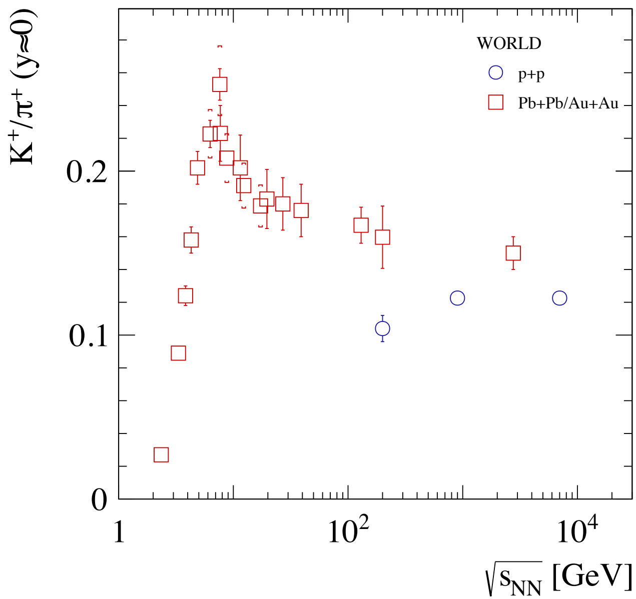
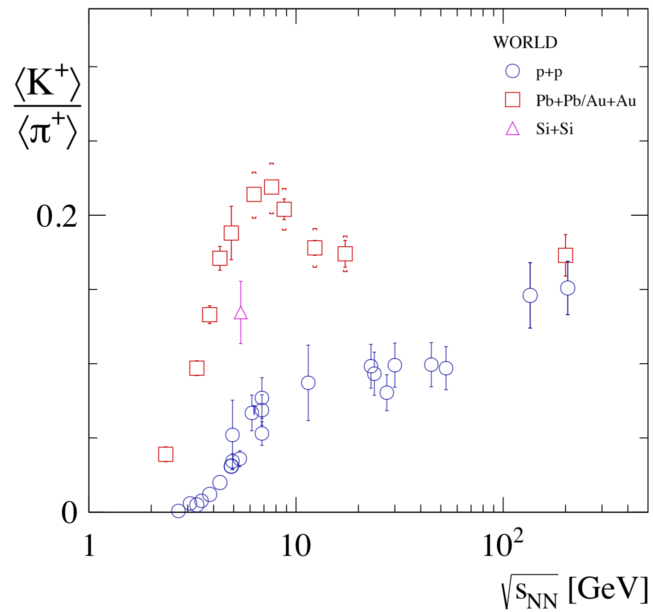
Signatures of the onset of deconfinement: horn





$\langle K^+/\pi^+\rangle$ ratio at mid-rapidity (left plot) and in whole phase space "4π" (on the right) in dependence on collision energy $\sqrt{s_{NN}}$

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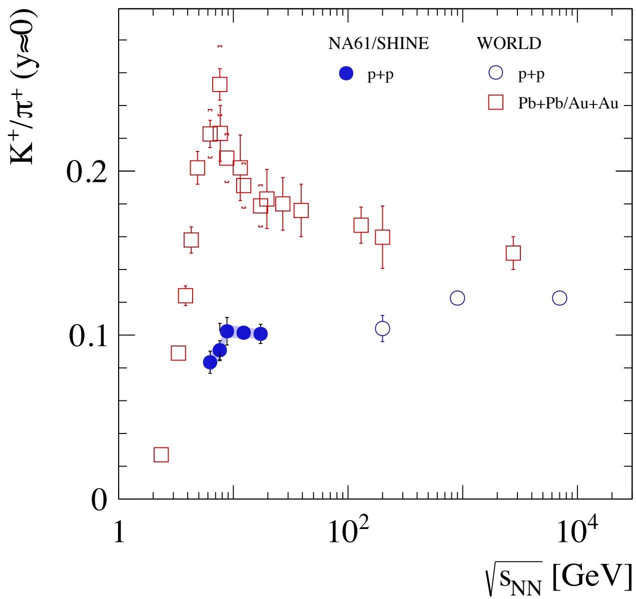

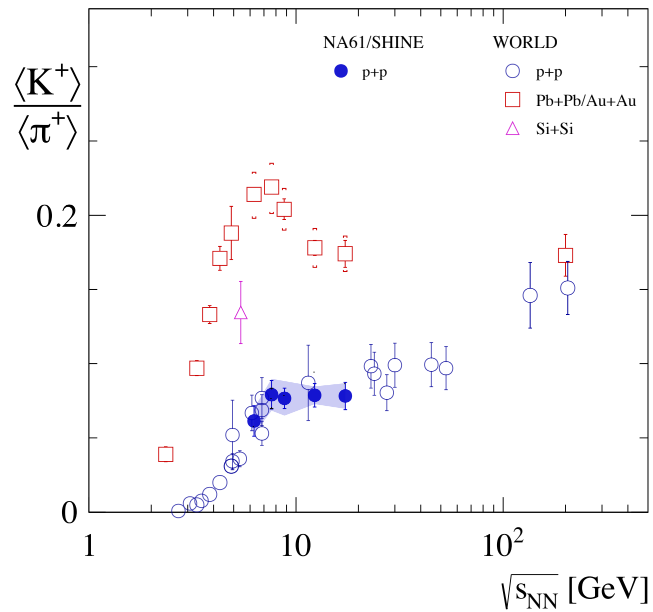

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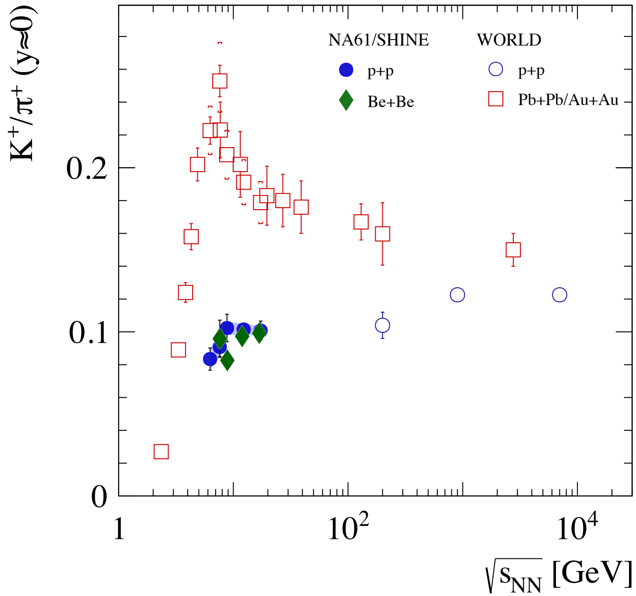
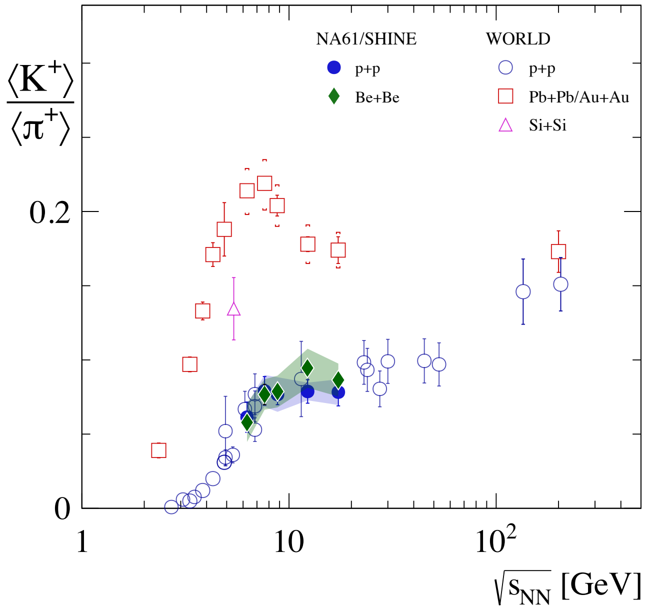
NA61/SHINE data:

p+p: Eur. Phys. J. C 77.10 (2017), p. 671, Eur. Phys. J. C 74.3 (2014), p. 2794.





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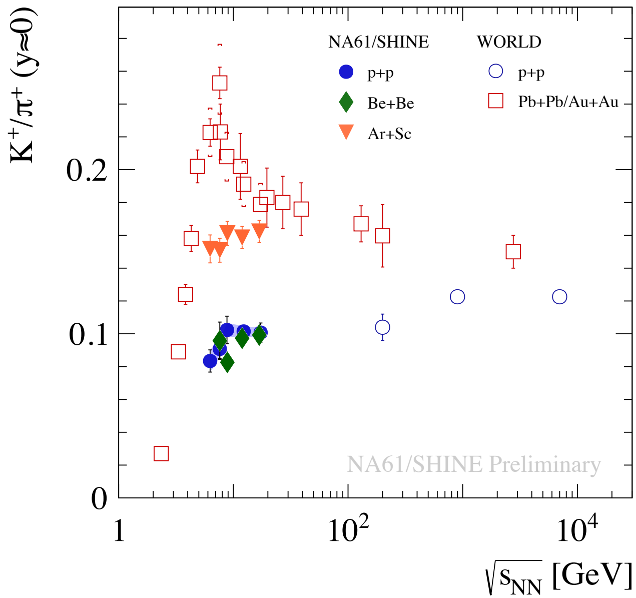

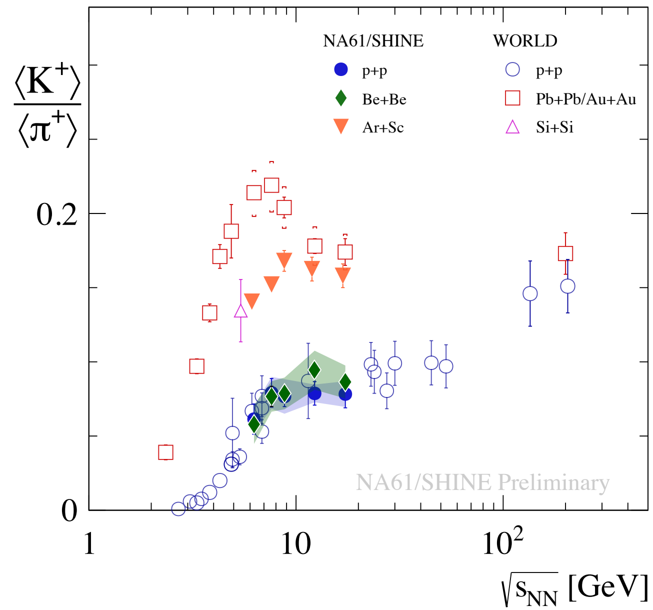

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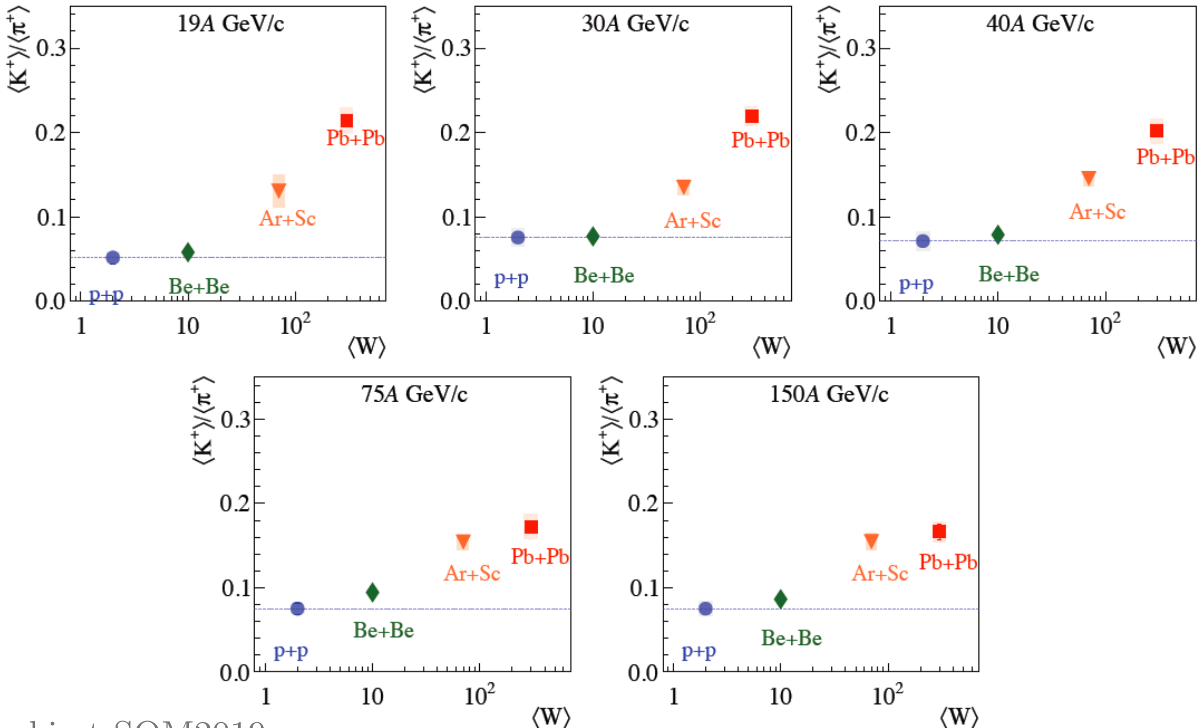
^{40}Ar+^{45}Sc: Eur. Phys. J. C 81.5 (2021), p. 397.

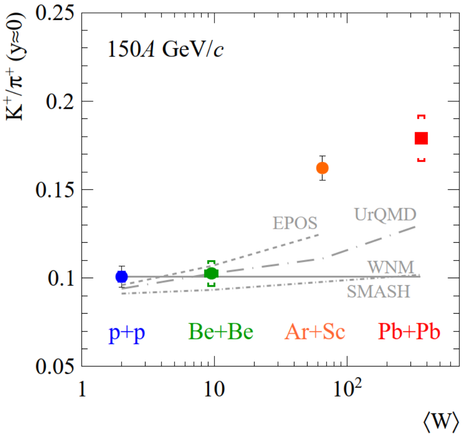
$\langle K^+\rangle/\langle\pi^+\rangle$ in whole phase space "4π" as a function of the system size

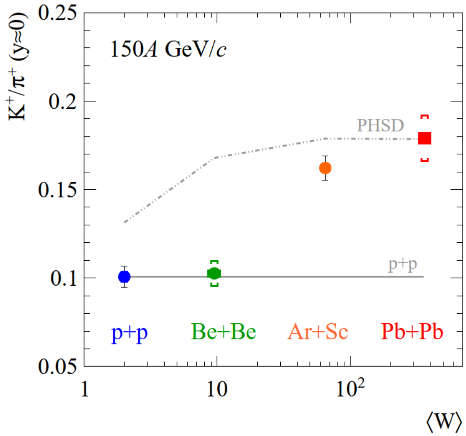


P. Podlaski at SQM2019

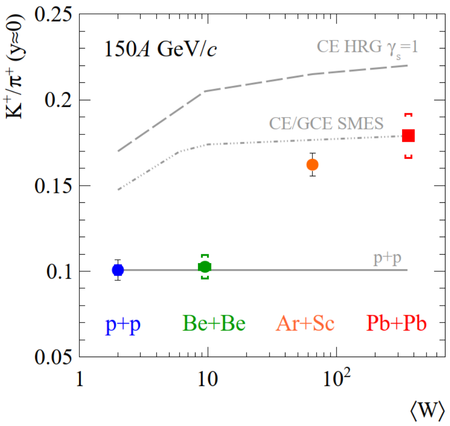
Ar+Sc data are closer to Pb+Pb than to p+p and Be+Be data.

Dynamical models





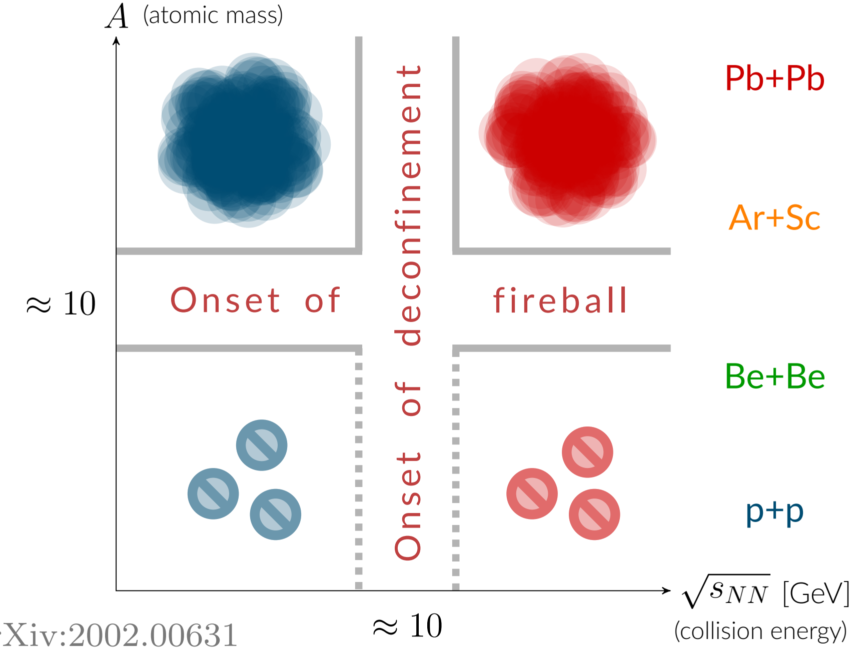
Statistical models



None of the models reproduce $\langle K^+\rangle/\langle \pi^+\rangle$ ratio for whole $\langle W\rangle$ range.

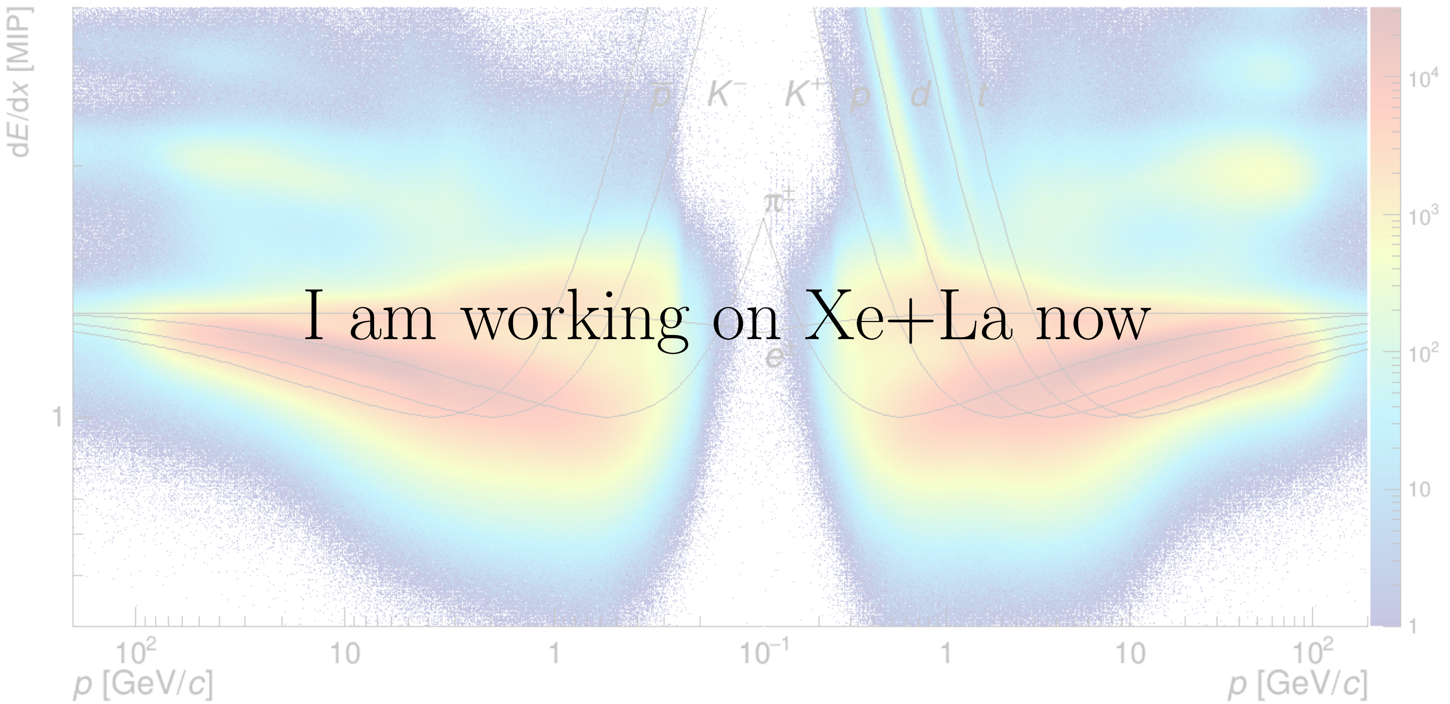
PHSD: Eur.Phys.J.A 56 (2020) 9, 223, arXiv:1908.00451 and private comunication;
SMASH: J.Phys.G 47 (2020) 6, 065101 and private comunication;
UrQMD and HRG: Phys. Rev. C99 (2019) 3, 034909
SMES: Acta Phys. Polon. B46 (2015) 10, 1991 - recalculated

Onset of fireball and onset of deconfinement



Lewicki, Turko, arXiv:2002.00631

Onset of deconfinement — the beginning of the creation of QGP in nucleus-nucleus collisions with increasing collision energy.
Onset of fireball — the beginning of the creation of large clusters of strongly interacting matter in nucleus-nucleus collisions with increasing mass number.



I am working on Xe+La now

Thank you for the attention!

Backup Slides

Layout of the NA61/SHINE experimental setup